Liquid Oxygen/Methane Propulsion for Exploration Systems Spacecraft

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Earth-storable propellants were successfully used in Gemini, Apollo, and shuttle programs. However, during the shuttle program, long-term issues with Earth-storable propellants such as valve corrosion and leakage, toxic propellant leakage, heater power, propellant freezing, and propellant cost and availability became more pronounced. These are not desirable characteristics as the basis for future robust exploration. A higher-performance, more operationally efficient, reliable, and safe propulsion system is needed for the lunar and Mars missions. Furthermore, using propellants compatible with in-situ resource utilization, power, and life support systems will increase flexibility for future mission architectures. The challenge is to determine which propellant best meets future needs, and which can be implemented with minimal risk to the program to support exploration missions. As shown in figure 1, it is useful to consider the duty cycle, thrust level, and total impulse of the different vehicles when choosing the optimum propellant for a given application.

A number of propellants have been evaluated for a service module or lander-type vehicle; oxygen, hydrogen peroxide, nitrogen tetroxide (NTO), with ethanol, methane, mono-methyl hydrazine (MMH), and hydrogen. Liquid oxygen (LO_2) based propellants for Orbital Maneuvering System (OMS), Reaction Control System (RCS), and lander/ascent

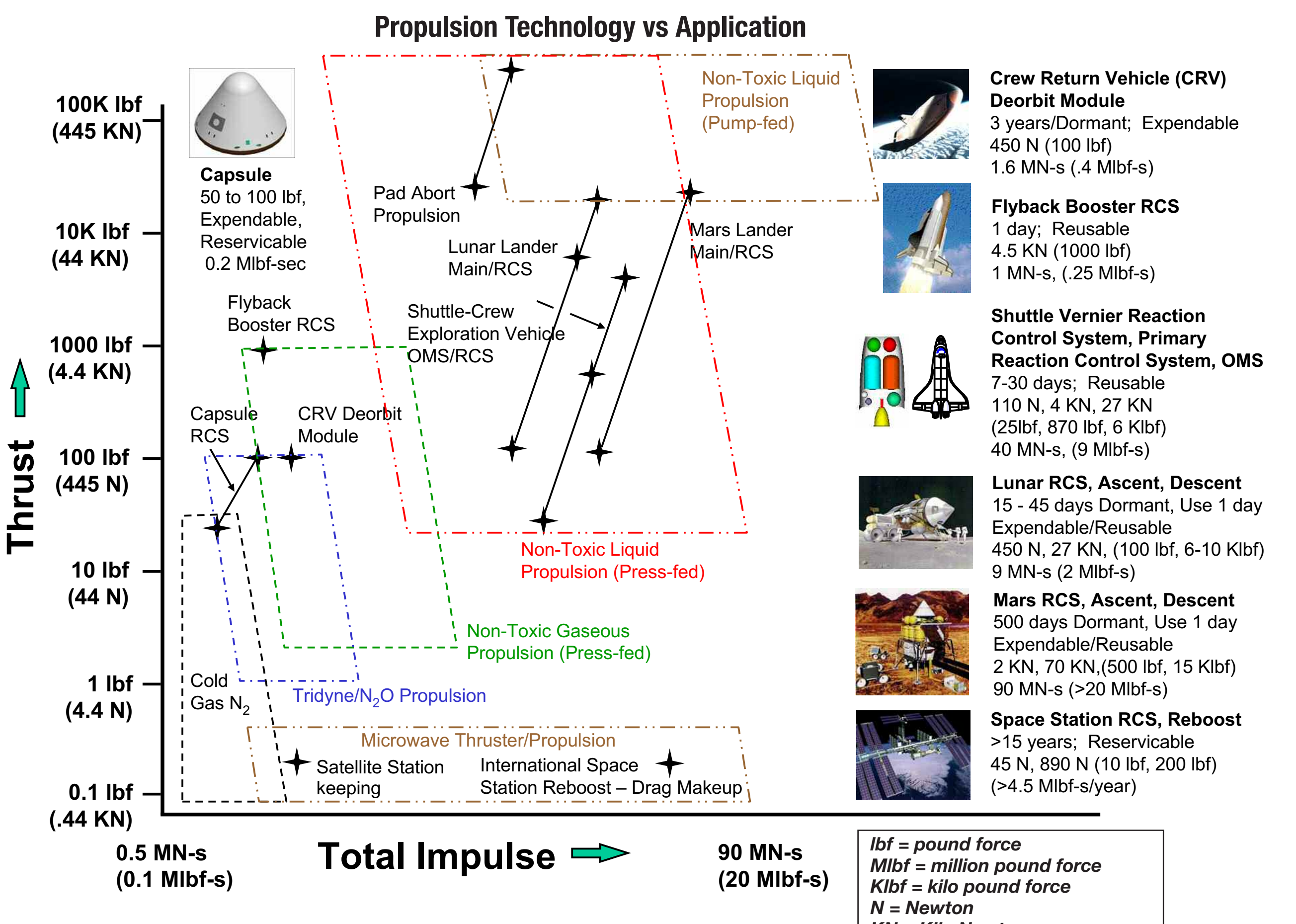

Fig. 1. Duty cycle, thrust level, and total impulse of various vehicles.

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descent have been identified as good candidates. The fuels best suited are ethanol and methane. This is due to the higher density, clean burning, and space-storable characteristics. The specific impulse advantage of liquid hydrogen (LH_2) does not offset the negatives associated with LH_2 storage. This and other trades showed that LH_2 results in a spacecraft that is twice as large and 33% more complex. Pressure-fed LO_2/methane actually performs comparable to the LO_2/LH_2 pump-fed. The reason for this is the higher dry mass of an LO_2/LH_2 system caused by the tank and structure mass. The hazards of hydrogen systems are a significant impact to the safety of a mission, and are worth a separate discussion. Hydrogen is prone to leakage due to its low temperature, small molecule, and difficulty in conducting leak tests. The shuttle main propulsion system has shown the difficulty in verifying leak-tight systems and finding hydrogen leaks. Furthermore, since LO_2/LH_2 must be pump-fed, the RCS gasification and OMS engine gas generators, heat exchangers will have more failure modes. One such failure mode would be leakage between shutdown of a propellant into the RCS gas generators. Restart would be hazardous unless purged well between runs. This will be a major safety concern for RCS, which performs a variety of duty cycles. Figure 2 shows a qualitative comparison of the propellants. The LO_2 is common with life support, power, and thermal control systems. A pressure-fed LO_2/methane saves mass overall compared to MMH/NTO, and offers additional cost, operational, safety, and vehicle integration benefits. Due to mass, safety, reliability, complexity, packaging, and performance reasons, a pump-fed LO_2/LH_2 system is not recommended for a service module or lander.

Relative Comparison of Propellants to MMH/NTO Systems Operability Assessment (SOA)

	MMH/NTO Pressure-Fed	H_2O_2/H-C Pressure-Fed	LOX/Alcohol Pressure-Fed	LOX/Methane Pressure-Fed	LOX/Methane Pump-Fed	LOX/LH_2 Pump-Fed
Performance						
Total Mass (specific impulse [Isp])	**SOA**	-	+	+	+	+
Power Required (Heaters)	**SOA**	-	+	+	+	+
Volume, (Density Isp)	**SOA**	+	+	-	+	-
Reliability and Safety						
Number of Components	**SOA**	+	+	+	-	-
Explosive Residues	**Need Improvement (Imp)**	+	+	+	+	+
Plume Contamination		-	+	+	+	+
Non-Corrosive	**Need Imp**	-	+	+	+	+
Low Leakage	**Need Imp**	+	+	+	+	-
Fast Response	**SOA**	+	+	+	-	-
Toxicity	**Need Imp**	+	+	+	+	+
Flammability	**Need Imp**	+	+	+	+	-
Cost						
Inert (Dry) Mass	**SOA**	+	+	+	-	-
Propellant Cost	**Need Imp**	-	+	+	+	-
Number of Components	**SOA**	+	+	+	-	-
Operations						
Long Term Storability (Years)	**SOA**	-	-	-	-	-
Propellant Management	**SOA**	-	+	+	-	-
Ground Propellant Handling	**Need Imp**	-	+	+	+	+
Integration w/Power/Environmental Control and Life Support System	**Need Imp**	-	+	+	+	+
Commonality with Human Exploration and Development of Space Roadmap	**Need Imp**	-	+	+	+	+
Total +		**9**	**18**	**17**	**13**	**9**

Fig. 2. Qualitative comparison of propellants. **+ = Better than NTO/MMH (or equal to if also good)** **− = Worse than to NTO/MMH**

Fig. 3. LO_2/ethanol and methane test article and engine firing.

A key technology is the development of an Integrated RCS and main engine cryogenic feedsystem. The advantages of a cryogenics RCS feedsystem are: 1) the reduction in size of valves and piping; 2) the elimination of Criticality 1 failures modes of gasification equipment; 3) the reduction in mass; and 4) the commonality of hardware and technologies to cryogenic tank storage. The disadvantage, of course, is the need to further develop engine technologies that allow the engine to rapidly start-up from ambient with warm gas and engine injector-to-valve thermal isolation. Other technologies to keep the valves pre-chilled can aid in a fast engine start-up.

Based on the energy that it takes to gasify propellants, it is simpler to insulate and deliver propellants as a liquid. In space, the vacuum is ideal. The key to using cryogenics RCS feedsystem is to highly sub-cool the propellants. A sub-cooled cryogenic RCS feedsystem uses multilayer insulation, flow of propellants caused by thruster usage, and possibly cryocoolers to keep the manifolds conditioned. The properties of LO_2 and methane allow them to be transferred and remain liquid even after absorbing much heat. Liquid methane that is stored at 275 psia and 163°R, is sub-cooled by 140°R. Actually turning liquid methane to a gas requires another 219 btu/lbm.

By comparing the thruster propellant usage rate and heat leak, it can be determined whether the feedsystem will remain chilled-in without venting. The heat leak into the feedsystem for a spacecraft needs to include lines, supports, valves, and engines. The Apollo Service Module (1970s) used, on average, about 3 lbm/hr of propellant. It is reasonable to expect that thruster usage will keep the lines chilled, and that minimal venting will be required. If venting is required to maintain propellant conditions, it is most efficiently done using a hermodynamic vent system attached to the feedline. The gases being vented can also be used for other purposes, such as environmental control and life support system, cold gas propulsion, or power, so as to not waste mass.

Cryogenic RCS feedsystem and engines have been under development since shuttle upgrades and next-generation launch technologies, and now currently are being developed by Propulsion and Cryogenics Advanced Development Team led by Glenn Research Center, with participation from other centers including Johnson Space Center (JSC). Breadboard testing of a cryogenic LO_2 RCS feedsystem at the JSC/Energy Systems Test Area demonstrated the capability to maintain subcooled propellants in the manifold near the thruster inlets using a thermodynamic vent system. Several 100-lbf RCS engine development contracts are building and testing hardware to demonstrate pulse-to-pulse repeatability, reliable ignition, and operation over a wide range of conditions. These feedsystems and engines are currently being tested at the White Sands Test Facility in New Mexico, as shown in figure 3.